OPTICAL FREQUENCY STANDARD DEVELOPMENT IN SUPPORT OF NASA'S GRAVITY-MAPPING MISSIONS

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Abstract

We have begun constructing all-solid-state laser systems at 778 nm and at 532 nm in support of a satellite-based gravity-mapping mission tentatively planned to fly in 2007. In each case the lasers will be stabilized at short times to high-finesse Fabry-Perot cavities similar to those of Ref. 1. At longer times the 778 nm laser will be stabilized to the 2-photon transition in rubidium [2,3]. In the 532 nm system, a frequency-doubled Nd:YAG laser with a non-planar ring oscillator (NPRO) design will be frequency-locked to a molecular iodine line [4]. We intend to combine the exquisite performance over short time scales coming from a cavity reference with the long-term stability of an atomic frequency standard with an eye towards reliability in a spaceflight application. By developing two separate candidate systems with proven performance we intend to maximize the probability of success for this mission-critical system development.

Motivation

The EX-5 mission is a follow-on to NASA's Gravity Recovery and Climate Experiment (GRACE), which will map changes in the Earth's mass distribution due, for example, to changes in the polar ice caps, large aquifers, and major ocean currents over its five-year mission lifetime. [5] The map is generated by precise ranging between two satellites separated by 50-100 km and flying in a low earth polar orbit. The GRACE metrology uses a microwave source derived from a 5 MHz quartz crystal oscillator specified to have Allan deviation $< 2 \times 10^{-13}$ from 1-100 s and $< 5 \times 10^{-13}$ out to 1000 s. The resolution of the metrology is expected to be limited by an on-board accelerometer as well as by oscillator noise. Improved performance of EX-5 will derive from an improved accelerometer design and an improved inter-satellite optical link. To support this improvement the lasers should have Allan deviation $< 1 \times 10^{-13}$ from 1-1000 s, but with the goal of significantly improved stability, carried out well beyond an orbit (5500 s). There is essentially no requirement on accuracy for these systems, provided the lasers on each spacecraft are close enough in frequency to make a useful beat note.

Approach

We have chosen a dual approach to meeting the needs of EX-5 and other NASA missions with the intention of maximizing both the performance and versatility of the capabilities being developed at JPL. The requirements on lasers to support these missions include a minimum five-year lifetime and low power consumption, making solid state lasers most attractive. NPRO lasers offer excellent short term stability as well as reliable operation, although feedback bandwidth to these lasers is limited to 30 kilohertz. Fabry-Perot style diode lasers have much larger linewidths, but feedback bandwidths can be in the MHz range, allowing performance better than that demonstrated for the NPRO lasers at short times [6]. By offering two different technologies, and stabilization over either fast time scales, slow times scales, or both, we hope to support the maximum range of future users.

The primary focus in the first stage of development is an NPRO laser system, frequency-doubled and locked to both a high-finesse optical cavity and to molecular iodine, as shown in Fig. 1. The doubled (532 nm) light will be locked 40 MHz off of an iodine resonance using common saturated absorption techniques. A 350 MHz acousto-optic modulator (AOM) in a double pass configuration will be used to shift the 532 nm light onto a cavity resonance for fast stabilization of the Pound-Drever-Hall type. Frequency corrections below 1 Hz will be made to the Nd:YAG crystal oven temperature, while corrections out to 30 kHz will go to the PZT on the crystal.

Frequency doubling of the NPRO laser is done using a periodically poled lithium niobate (PPLN) crystal in a single-pass configuration as shown in Fig. 2. Theoretically the PPLN crystal in single pass gives 20 times the conversion efficiency of ordinary lithium niobate, with more typical performance being a factor of two less than this. The theoretical efficiency is also twice the efficiency of potassium niobate, with

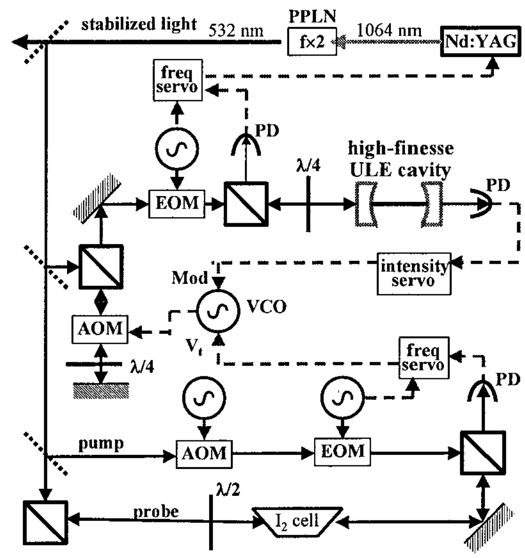

Figure 1. Design layout for frequency stabilization of the 1064 nm. The laser will be locked to an absorption line in molecular iodine. A 350 MHz AOM is used to frequency shift this light onto a cavity resonance for stabilization at short times.

one-quarter the temperature sensitivity and 1/40 the angular sensitivity. We do slightly worse than optimal, getting approximately 2 mW of 532 nm light with a FWHM in temperature of 2 °C with 500 mW of 1064 nm light.

The scheme shown in Fig. 1 shows the 1064 nm light from the NPRO laser filtered out, and the 532 nm light is shown as the stabilized light to be sent to the spacecraft. Since most of the power from the NPRO remains in the fundamental, we intend to explore the possibility of using the 1064 nm light as the output to the spacecraft. One component of these tests will be to use a high-finesse optical cavity with mirrors coated for 1064 nm to look at the short-term behavior, and also to compare the 532 nm light that has been stabilized directly to iodine with light that has been doubled in an independent crystal.

The second system under development utilizes a grating-stabilized

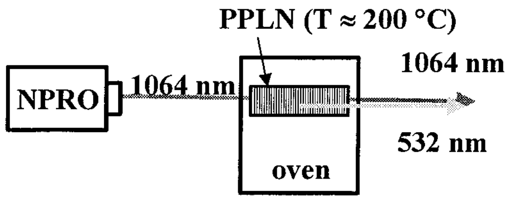

Figure 2. Frequency doubling using a periodically poled lithium niobate (PPLN) crystal.

diode laser at 778 nm locked to a cavity, as in the NPRO system, and also to a 2-photon transition in rubidium as in the literature [2,3]. Such systems have realized slightly worse performance than the iodine-stabilized NPROs, and the mechanically tuned laser may be difficult to qualify for long-term flight applications, so this system has been given lower priority than the NPRO. The benefit of increased feedback response (many MHz) may make them more attractive for applications interested predominantly in short term performance.

Status

We have finished designs of the optical cavities and of the lock electronics. All major system components have been procured but not fully implemented. We have verified the tuning characteristics of the NPRO laser and the performance of the PPLN doubler. We have observed iodine resonances. On the 778 nm system we have observed the two-photon transition on the various hyperfine components of ^{85}Rb and ^{87}Rb. Assembly of the optical cavities and the lock electronics are underway.

Over the three years of this task we intend to produce two independent NPRO systems, as well as two independent diode systems at 778 nm. The most promising candidate for supporting EX-5 and other NASA flight missions will begin development towards flight qualification at the end of the development period.

Acknowledgements

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